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CONTINUOUS EXPLOSIVE FRAGMENTATION TECHNIQUES

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Bureau of Mines In-House Research

Continuous Explosive Fragmentation Techniques

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13. ABSTRACT

This study is designed to improve the technology of the application of explosives to rapid excavation, particularly tunneling and mining in hard rock. Efforts during the year were concentrated on: (1) selection of suitable candidate explosives according to criteria based on considerations of (a) explosive performance, involving detonation rate and relative explosive energy measurements, and (b) safety, involving sensitivity tests and measurement of toxic fume production, and (2) investigation of potential initiation systems including primarily, projectile impact, laser and hypergolic liquid impingement as means of initiation. Explosive energy was determined by the expanding cylinder technique and by experiments in an underwater test facility. Detonation rates and casing expansion velocities were measured by the use of continuous velocity probes. Explosive sensitivity was measured by determining the susceptibility to initiation by a No. 6 electric blasting cap and by the projectile impact test. Toxic fume production rates were determined by firing the explosives in the Crawshaw-Jones apparatus. Laser initiation experiments were conducted using a pulsed ruby laser. Tests were conducted on four commercial dynamites, five experimental slurries, two commercial water gels, two commercial ammonium nitrate-fuel oil (AN-FO) mixes, and one commercial two-component system.

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CONTINUOUS EXPLOSIVE FRAGMENTATION TECHNIQUES

Technical Report Summary

Objective: This study is designed to improve the technology of the application of explosives to rapid excavation, particularly tunneling and mining in hard rock. Primary areas of research include development of jelled or slurry type explosives suitable for automatic injection into boreholes and feasibility studies of initiation systems alternative to conventional electric blasting caps for detonating these explosives.

Research Plan: One possible improvement in the technology of applying explosives to rapid excavation would be the incorporation of automated explosive injection with a novel initiation system into a continuous drill-load-blast machine having the potential for producing significant increases over current tunneling rates. The approach to the problem can be broken down into two separate but interrelated efforts: (1) the selection of jelled or slurry explosives suitable for atuomatic injection into boreholes, and (2) the development of a novel initiation system suitable for detonating the candidate explosive.

Major Accomplishments: Efforts during the year were concentrated on: (1) selection of suitable candidate explosives according to criteria based on considerations of (a) explosive performance, involving detonation rate and relative explosive energy measurements, and (b) safety, involving sensitivity tests and measurement of toxic fume production, and (2) investigation of potential initiation systems including primarily, but not exclusively, projectile impact, laser and hypergolic liquid impingement as means of initiation. Explosive energy was determined by the expanding cylinder technique (1) and by experiments in the Bureau's underwater explosive test facility (2). Detonation rates and casing expansion velocities were measured by the use of continuous velocity probes developed by the Bureau (3). Qualitative measurements of explosive sensitivity were made by determining the susceptibility to initiation by a No. 6 electric blasting cap; quantitative measurements were made using the projectile impact test (6). Toxic fume production rates were determined by firing the explosives in the Crawshaw-Jones apparatus (7) sampling and analyzing the products. Susceptibility to initiation by deflagration sources i.e., to deflagration to detonation transition, was measured in a simulated borehole consisting of a length of schedule 40 steel pipe, loosely capped and vented at the initiation end. Laser initiation experiments were conducted using a pulsed ruby laser.

Tests were conducted on four commercial dynamites, five experimental slurries, two commercial water gels, two commercial ammonium nitrate-fuel oil (ANFO) mixes, and one commercial two-component system. Results are summarized in tables 1 and 2.

TABLE 1

Summary of Results of Explosives Survey

Explosive Designation	Detonation Velocity (m/sec)	Casing Velocity (m/sec)	Shock Energy	Bubble Energy	I.M.E. Fume Class
		Commercial Dynamites			
P-1312	3820	560	88.1	91.9	2
D-1316 (40%)	4690	680	74.4	95.5	-
P-1308	5230	880	82.6	92.7	2
D-1351 (40%)	5560	770	92.7	105	1
		Experimental Slurries and Water Gels			
272-H	4110	600	105.2	127.4	1
270-H	4150	580	93.8	132.9	1
270-C	4300	660	90.0	123.8	1
272-C	4370	660	94.8	128.6	1
PB-1	6040	1230	159	209	-
		Commercial Water Gels			
P-1257	3290	440	46.0	69.2	2
P-1340	4860	790	74.6	94.2	1
		Commercial AN-FO			
X-1247	2370	510	72.8	90.4	1
X-1250	2510	480	74.6	87.5	1
		Commercial 2-Component			
X-1334	5760	970	110	106	1

TABLE 2

Summary of Results of Initiation Studies

Explosive Designation	V_{50} (m/sec)	#6 Cap Sensitivity	DDT
	Commercial Dynamites		
P-1308	~ 100	Yes	Yes
D-1316 (40%)	140	Yes	Yes
P-1312	154	Yes	Yes
D-1351 (40%)	170	Yes	Yes
	Experimental Slurries and Water Gels		
272-C	264	Yes	No
270-C	384	Yes	No
272-H	~ 400	Yes	No
270-H	~ 400	Yes	No
PB-1	969	No	-
	Commercial Water Gels		
P-1257	336	Yes	No
P-1340	410	Yes	No
	Commercial AN-FO		
X-1250	900	No	-
X-1247	~1000	No	-
	Commercial 2-Component		
X-1334	538	Yes	No

or slurry type explosives, suitable for automatic injection into boreholes, which also would have properties optimized for application to a continuous cyclic process in which boring, loading, firing, and muck removal would progress simultaneously at different parts of the working face, and (2) feasibility studies of initiation systems alternative to conventional electrical blasting caps for detonating these explosives. Emphasis is placed on explosive characteristics which lead to optimum safety and efficiency in automatic loading operations including, e.g., adaptability to automatic formulation from relatively inert ingredients at the working face, optimum explosive energy coupling characteristics, minimum toxic fume generation. Initiation systems considered include those using projectile impact, laser initiation, and hypergolic liquid impingement.

IV. Results to Date

Criteria for selection of suitable candidate explosives were based on considerations of performance and safety, involving measurement of detonation rate, three measures of relative explosive energy, two sensitivity tests and estimates of toxic fume generation.

One measure of relative explosive energy is determined using the expanding cylinder technique (1). The explosive is detonated in a 12-inch long, 1.0-inch i.d., 0.133-inch wall steel tube and the casing expansion velocity and detonation rate are measured using a Bureau-developed continuous velocity probe (3) as shown in figure 1. The casing velocity values can be converted into casing kinetic energy per unit mass of explosive, usually standardized relative to TNT, and as such is a measure of the close-range effectiveness.

The underwater energy test (2) provides two additional measures of explosive energy; lightly confined 950-gram charges are detonated under water at a depth of 3.5 meters, and the pressure profile of the shock wave produced in the water is measured by a piezoelectric pressure transducer. The energy contained in the shock wave is essentially proportional to the time integral of the square of the pressure (4). At the same time, a gas bubble is formed which oscillates with a period whose cube is proportional to the energy expended in creating the bubble (5). The shock energy is essentially a measure of the shattering power, while the bubble energy is related to the heaving action. Both can be standarized relative to TNT.

Qualitative measurements of explosive sensitivity were made by determining the susceptibility of 1.0-inch diameter unconfined charges to initiation by a No. 6 electric blasting cap. Quantitative measurements were made using the projectile impact test (5) in which the explosive sample is impacted by a 0.5-inch diameter by 0.5-inch long brass projectile fired from a smooth-bore gun, and the projectile velocity corresponding to a 50 percent probability of initiation (V_{50}) is measured.

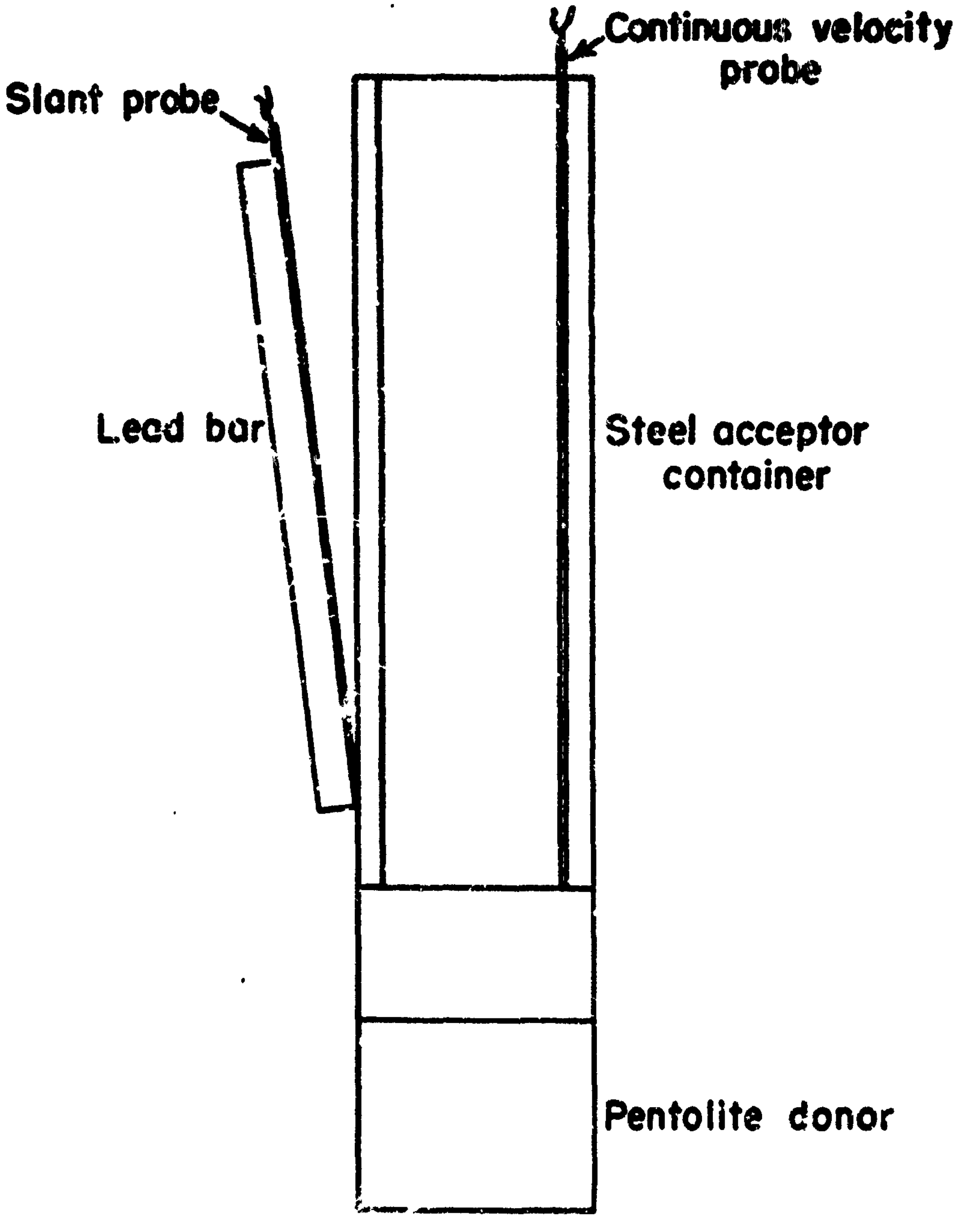

FIGURE 1. - Expanding Cylinder Test for Explosive Energy

Toxic fume determinations are made by firing the explosive in an evacuated 90-liter cylinder (Crawshaw-Jones apparatus (7)), and the products are analyzed and the explosives are classed according to recommendations of the Institute of Makers of Explosives: class 1 corresponds to less than 0.16 standard cubic feet (SCF) of toxic fumes per pound of explosive, class 2 to 0.16 to 0.33 scf/lb; and class 3 greater than 0.33 scf/lb. (Most states require explosives for underground use to be class 1.) Test results obtained with four commercial dynamites, five experimental slurries, two commercial water gels, two commercial ammonium nitrate fuel oil (ANFO) mixes and one commercial two-component system are summarized in tables 1 and 2. The general features of table 1 may be summarized as follows: detonation velocity, casing velocity, and shock energy as measured by the underwater test all correlate relatively well as expected except for the commercial water gels which yield low shock energies, and in one case low casing velocity. Bubble energies are relatively high for the experimental slurries and water gels, for which the afterburning of aluminum is an important contribution to the energy. As indicated by table 2 the projectile impact sensitivity correlates with the cap sensitivity and with susceptibility to deflagration-to-detonation transition (DDT): those explosives which have a V_{50} much in excess of 540 m/sec are insensitive to initiation to a No. 6 blasting cap; only those with a V_{50} less than 260 m/sec undergo DDT.

Judged by the above results, the most promising candidate explosives were: (1) among the commercial dynamites the one designated D-1351; this is a "40 percent extra dynamite" commonly used in hard rock blasting and has the highest shock and bubble energy of this class of explosives, good fume characteristics, and is relatively sensitive to initiation, as are all the dynamites, (2) among the experimental slurries and water gels the one designated PB-1 has excellent energy characteristics but is probably too insensitive to the remote initiation systems being considered; however, the one designated 272-C has good energy sensitivity and fume characteristics, and (3) among the commercial water gels, the one designated P-1340 has good energy, sensitivity, and toxic fume characteristics. The commercial two-component explosive X-1334 also has good energy sensitivity and toxic fume generation.

Several initiation systems were considered for application to the continuous explosive tunneling concept. These included the use of: (1) conventional electric, fuse-type and mechanically actuated ("stab") detonators, remotely initiated by radio frequency pulses or gas-phase detonations, (2) projectile impact, (3) initiation by laser or by (4) hypergolic liquid impingement. However, it was decided that the use of conventional detonators would not be economical with the short-hole blasting techniques envisioned, and the bulk of the research was directed to initiation techniques which do not rely on detonators, viz., mainly projectile impact, laser initiation, and hypergolic liquid impingement.

initiation of high explosives can generally be divided into two classes: (1) "direct" initiations, which involve run-up from a significantly supersonic shock wave to full detonation, usually in a few microseconds, and (2) deflagration to detonation transitions (DDT's) in which the reaction builds up from a subsonic combustion to the formation of a shock wave, usually over several milliseconds. "Direct" initiation can be achieved by projectile impact or by the evaporation shock generated by a Q-switched laser pulse (8) capable of power densities of the order of 10^9 w/cm^2. Without Q-switching power densities are typically a factor of 10^4 less; with these, or with hypergolic liquid impingement, only deflagrations can be initiated, and detonation thus depends on a DDT mechanism.

In order to explore the feasibility of DDT dependent initiation systems, several of the candidate explosives were tested in a simulated borehole consisting of a 16-inch length of 1-inch schedule 40 steel pipe loosely capped at both ends, with a venthole in the initiator end as shown in figure 2. A void in the initiator end was filled with 10 grams of powdered propellant which was ignited with an electric matchhead. The type of propellant employed does not matter much as long as mass burning rates of the order of 10^2 grams/sec/cm^2 of venting area are attained; for most of the work reported here, a finely shredded (100 mesh) ANP propellant (ammonium perchlorate, aluminum and synthetic rubber binder) was used, others included black powder, various kinds of smokeless powder, and powdered matchhead composition. It was found that only the commercial dynamites detonated with ventholes of realistic size (2.2 cm diameter) and all dynamites performed approximately the same in this respect. The other explosives underwent DDT only with ventholes of 0.3 cm or less, a condition which cannot be realistically extrapolated to actual boreholes. Thus, the dynamites at least can be considered compatible with DDT type initiation systems.

One potential method of remotely initiating an explosive is the impingement of a substance which is hypergolic with respect to the explosive, or of two substances which are hypergolic with respect to each other. The most familiar classes of hypergolic liquids are amines with nitric acid or nitrogen tetroxide. For preliminary experiments monomethyl hydrazine (MMH) and red fuming nitric acid (RFNA) (20% NO_2) were chosen. The DDT experiment was conducted in the same way as described above, except that the hypergolic liquids replaced the powdered propellant, as shown in figure 3. Four milliliters each of MMH and RFNA were used. Preliminary results were disappointing in that DDT resulted only with ventholes of 0.3 cm diameter or less, even with the dynamites. In practice some difficulty would be expected due to disruption of the liquid streams in flight; this could be minimized by using more viscid hypergolic fluids of higher surface tension, but at the expense of the rapid dispersion and mixing of the liquids which is essential to rapid deflagration. It is possible that more reactive practical systems can be found, perhaps by the addition of catalysts to the above system.

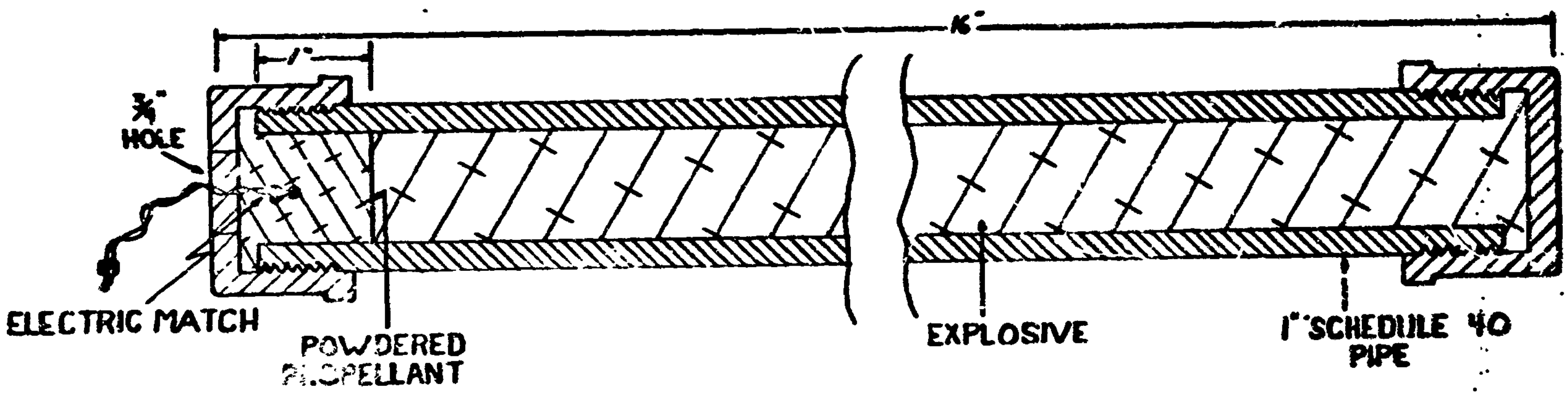

FIGURE 2. - Experimental arrangement used in deflagration to detonation transition experiments.

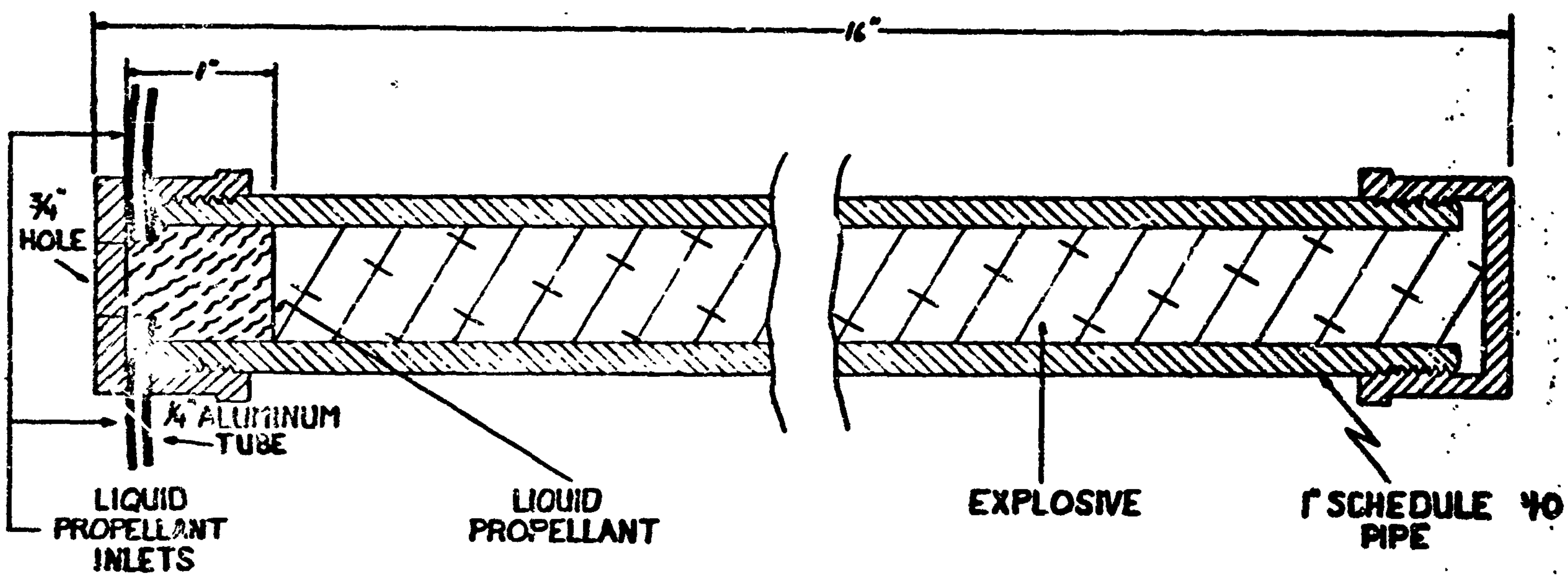

FIGURE 3. - Experimental arrangement used in hypergolic liquid initiation experiments.

Another potential remote initiation method is the use of high-intensity pulses of electromagnetic energy from a laser. Success in this area has already been achieved by Yang and Menichelli (8), using a Q-switched ruby laser. It can easily be demonstrated that the power densities necessary to generate shocks of the order of kilobars are of the order of 10^9 watts per cm^2, which can be attained only through Q-switching. Without Q-switching, power densities of the order of 10^5-10^6 w/cm^2 can be attained, but these would be expected to produce only deflagration, which could however transit to detonation.

The preliminary experiments performed here used a pulsed ruby laser with a measured output of 1.25 j. and a pulse width of ca 0.5 milliseconds. Various attempts were made to ignite the propellants used in the DDT experiment described above; these attempts were not successful in producing sustained ignition except for the matchhead composition. However, the principle is quite feasible.

More recent experiments on the initiation of explosives by projectile impact indicate that the dynamites at least can be initiated by relatively inexpensive standard .22 caliber ammunition. A summary chart indicating the feasibility of various initiation systems for the different types of candidate explosives is given in table 3.

This considerable advance toward the project objectives has been achieved. Future work in this area will concentrate on more detailed study of DDT and more extensive research on potential hypergolic systems and small caliber projectile impact initiation of other types of explosives.

TABLE 3

	Commercial dynamites	Experimental Water Gels	Commercial Water Gels	Commercial AN-FO	Commercial 2-Component
PROJECTILE IMPACT	Y	Y	Y	N	Y
LASER IGNITION	Y	N	N	N	N
HYPERGOLIC REACTIONS	Y	N	N	N	N
STAB DETONATORS	Y	Y	Y	N	Y
FUSE DETONATORS	Y	Y	Y	N	Y
GASEOUS DETONATIONS	?	?	?	N	?
OTHER	?	?	?	?	?

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